Chapter

13 ELECTROMAGNETISM

⇒ Electro = Electric current, Magnetism = magnet.

⇒ The relationship between magnetism and electricity was discovered in 1819 when, during a lecture demonstration, the Danish scientist Hans Christian Oersted found that an electric current in a wire deflected a nearby compass needle.

⇒ So, the production of magnetism from electric current is called electro magnetism.

⇒ Oersted for the first time concluded that when a charge is in motion then it produce magnetic field.

⇒ So, Charge at rest produce only 'Electric field'.

⇒ A charge in motion produce two fields. 'Electric field and Magnetic field'.

⇒ In nature there are three fields;

1. Electric field
2. Magnetic field
3. Earth gravitational field

⇒ Electric field surrounds the charge when it is at rest or in motion, magnetic field surrounds an object when it is in motion only, while gravitational field is surrounded by all objects.

⇒ So. a charge is surrounded by 3 fields.

⇒ In ***electromagnetism*** we study only electric and magnetic field of charge so here we neglect gravitational field and we consider that a moving charge is surrounded by two fields.

What is actually magnet?

The early Greeks knew about magnetism as early as 800 B.C. They discovered that the stone magnetite ($Fe3O4$) attracts pieces of iron. A magnet (from Greek word 'Magnesian Stone') is a material that produces magnetic field. This field is invisible. Permanent magnets and electromagnets are used in many every day and scientific applications. Huge electromagnets are used to pick up and move heavy loads, such as scrap iron at a recycling plant.

Iron objects are most strongly attracted to the ends of such a magnet. These ends are called poles; one is called the north pole, and the other is called the south pole.

Like poles repel each other, and unlike poles attract each other;

The magnetic force between two magnets can be likened to the electric force between charged objects in that unlike poles of two magnets attract one another and like poles repel one another. Thus, the north pole of a magnet is attracted to the south pole of another magnet, and two north poles (or two south poles) brought close together repel each other. Electric charges differ from magnetic poles in that they can be isolated, whereas magnetic poles cannot. In fact, no matter how many times a permanent magnet is cut, each piece always has a north pole and a south pole. Thus, magnetic poles always occur in pairs.

Important points

⇒ In case of a bar magnet, the density of magnetic field lines is high at points near the poles, and the density at points near the center of the magnet is low.

⇒ If we place a magnetic compass at any point in the earth's magnetic field, it will align itself in the direction of the magnetic field lines.

⇒ Common misconception about magnetic field lines is that it is the path followed by a magnetic north pole in a magnetic field.

⇒ This is not correct. It is the instantaneous direction of the magnetic force acting on the magnetic north pole in the magnetic field.

Oersted Discovery

i. He founds that if magnetic needle is parallel to conducting wire, this means that there is no current in the wire, so there is no deflection of magnetic needle.

ii. If current is flown through the wire, the magnetic needle is deflected, when again the current is flown in opposite direction the magnetic needle again deflected but in opposite direction. This deflection shows that with there exist some magnetic field outside wire.

iii. On increasing the current in wire deflection of magnetic needle increases.

This is a solid proof that, *Current, $I \propto$ magnetic field strength.*

Conventions for Representing the Direction of a Magnetic Field

In the plane of the page	⬆
Into the page	✖
Out of the page	●

Magnetic field

⇒ A region in which a magnetic force can be detected.

⇒ It is represented by magnetic lines of force.

⇒ Magnetic lines of force always form a close loop.

⇒ Magnetic field lines start from North pole of magnet and ends on South pole of the magnet.

⇒ Inside magnet the direction of magnetic field lines is from 'South to North'.

⇒ Outside magnet the direction of magnetic field lines is from 'North to South'.

⇒ Magnetic field around the charge will be disappears if current is switched off or charges stop moving.

Magnetic flux Density, Magnetic field strength, Magnetic induction

⇒ The strength of magnetic field is measured in terms of Magnetic flux density.

⇒ $\vec{B}$ is a measure of field concentration (Number of lines in each square meter of the field).

⇒ The magnetic field around a current carrying conductor is described in terms of $\vec{B}$

⇒ It is represented by $\vec{B}$.

⇒ It is a vector quantity.

⇒ It is sometime called Magnetic field $\vec{B}$.

⇒ ***Unit:***

$$Tesla \quad or \frac{Wb}{m^2} \quad or\ Gauss$$

$$1\ Tesla = 10^4 G$$

$$1\ G = 10^{-4} T$$

Definition of magnetic field in term of (Force on a moving charge in magnetic field)

⇒ We can define a magnetic field B at some point in space in terms of the magnetic force FB that the field exerts on a charged particle moving with a velocity v, which we call the test object.

⇒ If $'q'$ is the charge moving in a uniform magnetic field $\vec{B}$ with speed $\vec{v}$, where θ is the angle between $\vec{v}$ *and* $\vec{B}$, so the force $\vec{F_m}$ exerted by magnetic field is given by;

$$F_m = qvB\ sin\theta$$

$$this\ shows\ that\ F_m \propto q\ (Magnitude\ of\ charge)$$

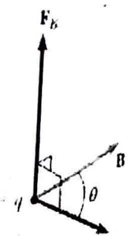
$$F_m \propto v\ (Magnitude\ of\ velocity)$$

$$F_m \propto B\ (strength\ of\ magnetic\ field)$$

$$F_m \propto sin\theta$$

In vector form;

$$F_m = q\,(\vec{v} \times \vec{B})$$



Note that $\vec{F_m}$ is perpendicular to plane of $\vec{v}$ *and* $\vec{B}$.

⇒ F_m *is perpendicular to* $\vec{v}$.

⇒ F_m is perpendicular to $\vec{B}$.

⇒ A uniform magnetic field can neither speed up nor slow down a moving charge particle, but it can change only direction of moving charge particle.

⇒ A magnetic force cannot change the kinetic energy of a particle.

⇒ $if\ v = 1, q = 1, \theta = 90°, then\ F_m = B$

$This\ shows\ that\ \vec{B}\ at\ a\ point\ in\ a\ space\ (2D) is\ equal\ to\ Force\ experienced\ by\ a\ unit\ positive\ charge\ moving\ with\ a\ unit\ velocity\ perpendicular\ to\ the\ direction\ of\ \vec{B}$

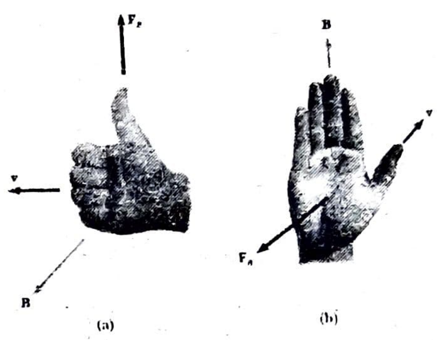
⇒ ***Direction of Magnetic force:***

It is given by two Right hand Rule:

Two right-hand rules for determining the direction of the magnetic force acting on a particle with charge q moving with a velocity v in a magnetic field B.

(a) In this rule, the fingers point in the direction of v, with B coming out of your palm, so that you can curl your fingers in the direction of B. The direction of $v \times B$, and the force on a positive charge, is the direction in which the thumb points.

(b) In this rule, the vector v is in the direction of your thumb and B in the direction of your fingers. The force FB on a positive charge is in the direction of your palm, as if you are pushing the particle with your hand.



⇒ If we apply the right-hand rule on electron (negatively charged), so by applying the rule it is clear that force on electron will be vertically upward.

⇒ The direction of positive charge will be exactly opposite, so it will be vertically downward for positive charge.

⇒ ***Some cases of Magnetic force;***

$$Sin(0°) = 0$$

$$Sin\ (180°) = 0$$

$$Sin(90°) = 1$$

Angle between $\vec{v}$ and $\vec{B}$	Magnetic force
1. $if\ \theta = 0°\ or\ 180°$	$F_m = qvB(0) = 0$
2. $if\ \theta = 90°$	$F_m = qvB(1) = qvB(maximum\ value)$

⇒ If $\vec{v} = 0$, i.e. charge particle is at rest

$$F_m = q(0)Bsin\theta = 0$$

Charge at rest experience no force.

⇒ If $q = 0\ then\ F_m = 0$

It means that electrically neural particles like neutron moving in magnetic field experience no force.

⇒ ***Unit of $\vec{B}$:***

Si unit of magnetic field $\vec{B}$ is Tesla.

As;

$$F_m = qvBsin\theta \Rightarrow B = \frac{F_m}{vqsin\theta}$$

$$if\ v = 1ms^{-1}, q = 1\ and\ F = 1N\ then\ B = 1Tesla$$

✓ Magnetic field of earth is about $10^{-4}T$.

✓ A strong electromagnet can produce a magnetic field of about 2 Tesla.

✓ Another unit used for B is Gauss.

$$1\ Tesla = 10^4 G$$

$$1\ Gauss = 10^{-4}T$$

Discussion

1. If $\theta = 0°$ then $F_m = qvB = 0$
   In this case B does not exerts any force on a charged particle. In this case a charged particle will move parallel to field.
2. If $\theta = 180°$ then $F_m = qvB = 0$

So, the particle will move in its original direction.

If $\theta = 90°$ then $F_m = qvB \Rightarrow Maximum\ value$

In this case a magnetic field will exerts force, not by changing magnitude of charge but it will do so by changing its direction, ***as a result the charged particle will move in a*** circle of radius r perpendicular to the field.

In such case magnetic force provides necessary centripetal force $= mv^2/r$

$$qvB = \frac{mv^2}{r}$$

i. ***Radius of a path:***

$$qvB = \frac{mv^2}{r} \Rightarrow r = \frac{mv}{qB}$$

$$r \propto v \Rightarrow fast\ moving\ particles\ move\ in\ large\ circl; e\ and\ so\ on$$

ii. ***Time period of revolution of charge particle in magnetic field:***

$$T = \frac{2\pi r}{v} = \frac{2\pi}{v} \times \frac{mv}{qB} = \frac{2\pi m}{qB}$$

$$Time\ period\ is\ independent\ of\ v\ and\ r$$

iii. ***Frequency of revolution in a circle:***

$$f = \frac{1}{T} = \frac{qB}{2\pi m}$$

iv. ***Angular frequency:***

$$\omega = 2\pi f = 2\pi\left(\frac{qB}{2\pi m}\right) = \frac{qB}{m}$$

4. If a moving charged particle enter a uniform magnetic field making an angle to the direction of field it describes a ***helical path.***

Concept

$$if\ \theta = 0° \Rightarrow then\ it\ mean\ something\ parallel$$

$$if\ \theta = 180° \Rightarrow then\ it\ mean\ something\ anti-parallel$$

$$if\ \theta = 90° \Rightarrow then\ it\ mean\ something\ Perpendicular$$

Magnetic flux

⇒ The dot product of magnetic induction B and vector area element ΔA.

$$\Delta\phi = B.\Delta A = B\Delta A\cos\theta \quad So;$$

$$B = \frac{\phi}{A} \Rightarrow Mgnetic\ field\ strength\ is\ magnetic$$

flux passing per unit area.

⇒ It is represented by ϕ.

⇒ The $\Delta\phi$ represents the magnetic field lines passing through the vector area element ΔA placed perpendicular to the field.

⇒ The area here is a vector area.

⇒ Direction of a vector area $\vec{A}$ is normal to the surface area.

⇒ ***Maximum magnetic flux:***

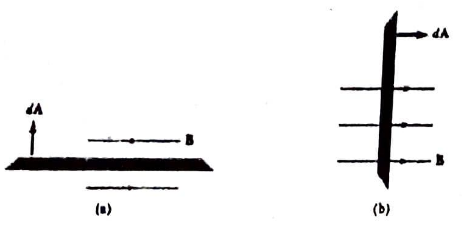
If the surface area is perpendicular to the field or Normal to the surface area is parallel to magnetic field B.

⇒ ***Zero Magnetic flux:***

If normal to the surface area become perpendicular to magnetic field B.

⇒ ***Unit:*** weber and $1\ Wb = 1NmA^{-1}$

Magnetic force on a current carrying conductor



Magnetic flux through a plane lying in a magnetic field
(a) The flux through the plane is zero when the magnetic field is parallel to the plane surface
(b) The flux through the plane is a maximum when the magnetic field is perpendicular to the plane

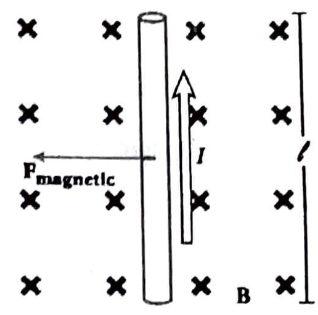
⇒ If a magnetic force is exerted on a single charged particle when the particle moves through a magnetic field, it should not surprise you that a current-carrying wire also experiences a force when placed in a magnetic field.

⇒ This follows from the fact that the current is a collection of many charged particles in motion; hence, the resultant force exerted by the field on the wire is the vector sum of the individual forces exerted on all the charged particles making up the current.

⇒ Magnetic force on a current carrying conductor is given by;

$$F = I(\vec{l} \times \vec{B})$$

$$F = IlB\ sin\theta$$



A current-carrying conductor in a magnetic field experiences a force that is perpendicular to the direction of the current

⇒ $\vec{l}$ is a vector length and direction of l is along direction of length

⇒ Note that this expression applies only to a straight segment of wire in a uniform magnetic field.

⇒ *Force per unit length is given by;*

$$\frac{F}{l} = IBsin\theta$$

⇒ Magnetic force on a current carrying conductor in different cases;

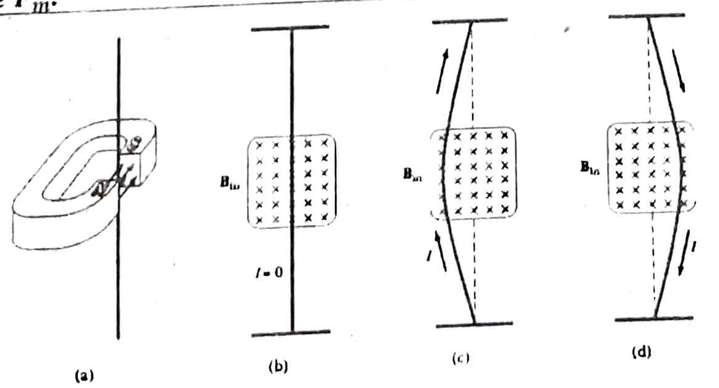
Angle	Magnetic force
1. *if* $\theta = 0°$ (*if a current carrying conductor is Parallel to* $\vec{B}$) *or* 180°. (*if a current carrying conductor is Anti Parallel to* $\vec{B}$)	$F_m = IlB(0) = 0$
2. *if* $\theta = 90°$ (*Perpendicular*)	$F_m = IlB(1) = IlB$ (*maximum value*)

⇒ ***Direction of force on a current carrying conductor:***

Hence, we know that $\vec{F}$ is always perpendicular to the plane of $\vec{l}$ *and* $\vec{B}$.

Its direction can be determined by one of the two rules;

Right hand rule for cross product	*Fleming's left hand rule*
Orient your right hand in such a way that your un-stretched finger points along the direction of conventional current, your bend fingers points along the direction of $\vec{B}$. ***Your extended thumb will give you direction of magnetic force*** $\vec{F_m}$.	Stretch forefinger, middle finger, and thumbs of your left hand mutually perpendicular. If forefinger points in the direction of $\vec{B}$ Middle finger in the direction of Current I ***Then thumb will give you direction of*** $\vec{F_m}$.



(a) A wire suspended vertically between the poles of a magnet.
(b) The setup shown in part (a) as seen looking at the south pole of the magnet, so that the magnetic field (crosses) is directed into the page. ***When there is no current in the wire, it remains vertical.***

(c) When the current is upward, the wire deflects to the left.
(d) When the current is downward, the wire deflects to the right.

Ampere's Law:

⇒ Ampere's law gives us general relation between a current in a wire of any shape and their magnetic field produced around it.
⇒ This law is only true for steady current.
⇒ The sum of dot product of magnetic field strength/Induction around any closed path in air/vacuum is equal to μ_o times the total current enclosed by that closed path.
⇒ The closed path is generally called Amperian loop (an imaginary closed loop of an arbitrary shape which enclosed current carrying conductor).
⇒ This law is only valid for symmetrical arrangements.

Permittivity = Electric property
Permeability = Magnetic property

Mathematical form:

$$\sum \vec{B}.\Delta\vec{l} = \mu_o I_{enclosed}$$

$$\mu_o = Permeability$$

⇒ The results hold good and is independent of shape and size of a close path that enclose current.
⇒ By considering a long straight current carrying conductor. Due too current magnetic field produced around the current carrying conductor, the magnitude of magnetic field that is perpendicular at a distance 'r' from conductor is given by;

$$B \propto I$$

$$B \propto \frac{1}{r}$$

$$B = \frac{\mu_o I}{2\pi r}$$

Note that $\mu_o/2\pi$ is a constant term.
⇒ This is one of the applications of ampere law.
⇒ Magnitude of magnetic field when there is external medium,

$$B_m = \frac{\mu_m I}{2\pi r} = \frac{\mu_r \mu_o I}{2\pi r}$$

⇒ **Permeability:** it is capability of a medium to be magnetized in external magnetic field.

$$\mu_o \rightarrow permeability\ of\ air\ or\ vacuum$$

$$\mu_m \rightarrow permeability\ of\ medium$$

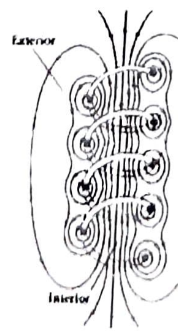
Relative permeability: the ratio of permeability of medium to permeability of vacuum.

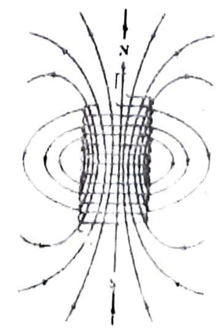
$$\mu_{relative} = \frac{\mu_m}{\mu_o}$$

$$Ratio: \frac{B_1}{B_2} = \frac{I_1}{I_2}$$

$$\frac{B_1}{B_2} = \frac{r_2}{r_1}$$

Magnetic field due to a current carrying solenoid (Application of Ampere law)





Magnetic field lines for a tightly wound solenoid of finite length, carrying a steady current. The field in the interior space is strong and nearly uniform. Note that the field lines resemble those of a bar magnet, meaning that the solenoid effectively has north and south poles.	The magnetic field lines for a loosely wound solenoid

⇒ Solenoid is a Greek word which means "tube like".

⇒ A solenoid is a long wire wound in the form of a helix.
⇒ Figure shows a current carrying solenoid.
⇒ Magnetic field around solenoid behaves like a bar magnet.
⇒ Inside magnetic field is uniform and parallel to the solenoid axis.
⇒ Outside the solenoid the magnetic field is very small.
⇒ As the length of the solenoid increases, the interior field becomes more uniform and the exterior field becomes weaker.
⇒ Magnetic field around current carrying solenoid is given by;

$$B = \mu_o n I$$

$$I = current\ through\ a\ solenoid$$

$$n = number\ of\ turn\ per\ unit\ length,$$

$$n = \frac{N}{l}$$

$$B = magnetic\ field\ inside\ the\ solenoid$$

⇒ Note that magnetic field inside solenoid is uniform.
⇒ Magnitude of magnetic field inside solenoid, when an iron core is placed inside it then;

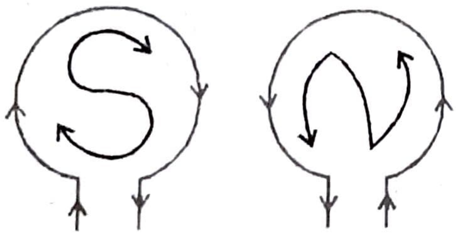
$$B = \mu_r \mu_m n I$$

⇒ By the use of iron as a core material (material inside solenoid) the overall magnetization or B_{net} will be increased
because core material adds some extra magnetic property.
⇒ At a point near the ends of an air-cored solenoid, the magnitude of magnetic field is given by;

$$B = \frac{1}{2}\mu_o n I$$

Keep in memory

If in a coil the current is clockwise, it acts as a South-pole. If the current is anticlockwise, it acts as North-pole.



Force between two current carrying conductor

⇒ If two current carrying conductors of same length carrying current in the same direction, they will show *attraction*. The force of attraction per unit length is given by;

$$F = \frac{\mu_o}{2\pi}\frac{I_1 I_2}{r}$$

⇒ If current in parallel conductors are in opposite direction the conductor will *repel* each other.
⇒ ***So, we can say that like currents attract and unlike current repel each other.***
⇒ ***Force between two parallel moving charges is given by;***

$$F = \frac{\mu_o}{2\pi}\frac{q_1 q_2 v_1 v_2}{r^2}$$

There are several important differences between electric and magnetic forces:

1. Source of electric force is source charge where source of magnetic force is current element.
2. Electric lines of force donot forms a close loop where magnetic lines of force can form a close loop.
3. Electric force is angle independent and magnetic force is angle dependent.
4. An electric force acts along the direction (parallel) of the electric field, whereas the magnetic force acts perpendicular to the magnetic field.
5. The electric force acts on a charged particle regardless of whether the particle is moving or at rest, whereas the magnetic force acts on a charged particle only when the particle is in motion.

6. The electric force does work in displacing a charged particle, whereas the magnetic force associated with a steady magnetic field does no work when a particle is displaced because the force perpendicular to the displacement.
7. ***This means that electric force changes the speed and hence kinetic energy. However, magnetic force does not change speed (kinetic energy) of charge particle.***
8. Note that the electric force is much greater than the magnetic force.

A long wire carrying a steady current. It is bent into a circle of one turn and the magnetic field at center of the coil is B. It is then bent into a circular loop of n turns. the magnetic field at the center of the coil will be

a) $2nB$ b) n^2B c) nb d) $2n^2B$

Magnetic field at the center of a circular coil of n turns is given by

$$B = \frac{\mu_o nI}{2R}$$

$$Thus\ B \propto N/R\ if\ current\ is\ constant$$

$$Given: n \times (2\pi r) = 2\pi R$$

$$R = nr\ or\ r = R/n$$

$$B' \propto n/(R/n)$$

$$B' \propto n^2/R$$

$$Thus\ B'/B = n^2 B$$

Lorentz force

⇒ The total force experienced by a charged particle moving in a region of space where both electric and magnetic fields are presents.

⇒ ***Mathematically it is given by;***

$$\vec{F}_{Lorentz} = \vec{F_e} + \vec{F_B} = q(\vec{E} + \vec{v} \times \vec{B})$$

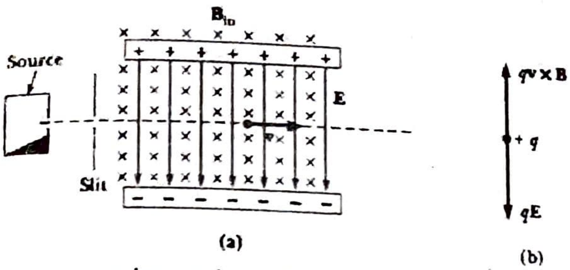
⇒ Some important cases;

	if $\vec{v}, \vec{E}$ and $\vec{B}$ are collinear		
Angle	*Magnetic force*	*Electric force*	*Result*
$if\ \theta = 0°\ or\ 180°$	$\vec{F_m} = 0$	$\vec{F_E} = qE$	In this case charge particle will experience only electric force, the speed, momentum and kinetic energy of a charged particle will be changed.

	if $\vec{v}, \vec{E}$ and $\vec{B}$ are mutually perpendicular		
Angle	*Magnetic force*	*Electric force*	*Result*
$if\ \theta = 90°$	$\vec{F_m} = -\vec{F_E}$	$\vec{F_E} = -\vec{F_B}$	In this case $\vec{F_L} = 0$ or $\vec{F_e} + \vec{F_m} = 0$ This means that if they are opposite to each other the particle will move undeflected through the field. i.e. $qE = qvB = v = \frac{E}{B}$

if velocity of a charged particle satisfies the equation $v = \frac{E}{B}$ *then it will go undeflected.*

Velocity selector



(a) A velocity selector. When a positively charged particle is moving with velocity v in the presence of a magnetic field directed into the page and an electric field directed downward, it experiences a downward electric force qE and an upward magnetic force $qv \times B$. (b) When these forces balance, the particle moves in a horizontal line through the fields.

⇒ In many experiments involving moving charged particles, it is important that the particles all move with essentially the same velocity. This can be achieved by applying a combination of an electric field and a magnetic field oriented as shown in Figure.

⇒ A uniform electric field is directed vertically downward (in the plane of the page), and a uniform magnetic field is applied in the direction perpendicular to the electric field (into the page).

⇒ If q is positive and the velocity v is to the right, the magnetic force $qv \times B$ is upward and the electric force qE is downward.

⇒ When the magnitudes of the two fields are chosen so that qE = qvB, the particle moves in a straight horizontal line through the region of the fields. From the expression qE = qvB, we find that

$$v = \frac{E}{B}$$

⇒ Only those particles having speed v pass undeflected through the mutually perpendicular electric and magnetic fields.

⇒ The magnetic force exerted on particles moving at speeds greater than this is stronger than the electric force, and the particles are ***deflected upward.***

⇒ Those moving at speeds less than this are ***deflected downward.***

Charge to mass ratio for an electron

Ratio generally means, let

$$\frac{x}{y} \text{ we have to find ratio between these variables.}$$

Generally, there will be three possibilities.

$$\frac{x}{y} > 1 \Rightarrow if\ x > y$$

$$\frac{x}{y} = 1 \Rightarrow if\ x = y$$

$$\frac{x}{y} < 1 \Rightarrow if\ x < y (the\ answer\ will\ be\ in\ points)$$

Ratio generally means that how much one variable is greater or equal or lesser than the 2nd variable.

⇒ ***In charge to mass ratio of electron,*** we determine whether charge of electron greater than its mass, equal to its mass or lesser than its mass.

⇒ ***The charge to mass ratio of an electron is given by;***

$$\frac{e}{m} = \frac{V}{Br} \quad or \quad \frac{e}{m} = \frac{2V}{B^2r^2}$$

$$V = potential\ difference\ applied$$

$$r = radius(magnitude\ of\ radius\ can\ be\ found\ experimentally)$$

⇒ Today, the accepted value of charge to mass ratio for an electron is; $1.7588 \times 10^{11} C.kg^{-1}$

MCQ: Order of e/m ratio of proton, α - particle and electron__________?

a) $(e/m)p > (e/m)\alpha > (e/m)e$

b) $(e/m)e > (e/m)p > (e/m)\alpha$

c) $(e/m)\alpha > (e/m)e > (e/m)p$

d) none of these

Electrical charge on proton, α-particle and electron is e, 2e, e, and $m\alpha = 4\,mp >> me$

$$\left(\frac{e}{m}\right)_p = \frac{3}{m\frac{a}{4}} = \frac{4e}{ma}$$

$$\left(\frac{e}{m}\right)_\alpha = \frac{2e}{ma}$$

$$So, \left(\frac{e}{m}\right)_p > \left(\frac{e}{m}\right)_\alpha$$

$$Hence, \left(\frac{e}{m}\right)_e > \left(\frac{e}{m}\right)_p > \left(\frac{e}{m}\right)_\alpha$$

Answer: (b)

Cyclotron

⇒ It is a device to accelerate heavy charged particles like proton, deuteron etc... to high speed.

⇒ It is only suitable for accelerating heavy charge object, electrons are not accelerated through cyclotron.

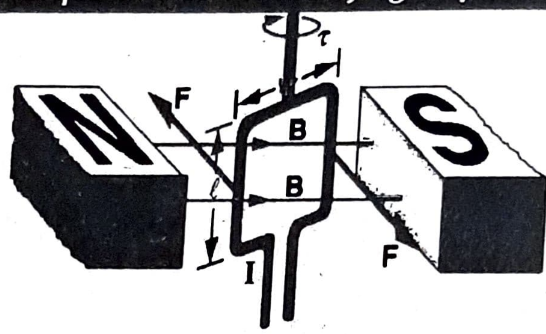
⇒ Uncharged particles like Neutron are also not accelerated through cyclotron.

⇒ ***Cyclotron frequency is given by;***

$$f = \frac{1}{T} = \frac{qB}{2\pi m}$$

Cyclotron frequency is independent of velocity v of ions and radius r of the circular path.

Torque on a current carrying loop or coil



⇒ When a current carrying loop is placed in a uniform magnetic field, a net torque acts on loop which tend to rotate the loop.

⇒ There are two forces that acts on loop, these forces are equal in magnitude ($= IlB$) but opposite in direction and have different line of action.

⇒ Therefore, these two forces constitute a couple which rotates the loop in anticlockwise direction about the vertical axis.

⇒ The torque on the loop is equal to moment of the couple.

⇒ ***Expression of torque acting on current carrying loop (Valid for loop of any shape):***

$$\tau = IABcos\theta$$

$$A = Area\ of\ loop\ (length \times bredth)$$

$$B = magnetic\ field\ in\ which\ loop\ is\ placed$$

$$I = current\ through\ loop$$

⇒ ***Expression of torque acting on current carrying loop for n turns (Valid for loop of any shape):***

$$\tau = nIABcos\theta = \frac{N}{l}IABcos\theta$$

$$where\ n = number\ of\ turns\ per\ unit\ length$$

⇒ ***Expression of torque acting on current carrying loop (if the loop is in circular shape):***

$$\tau = NIAB \Rightarrow NI\pi r^2 Bcos\alpha \Rightarrow NI\frac{\pi r^2}{4}Bcos\alpha \qquad As, Area = \pi r^2 = \frac{\pi D^2}{4}$$

Discussion

$\tau \propto$ Current through the loop

$\tau \propto$ area of coil or loop

$\tau \propto$ Magnetic field through the loop

$\tau \propto$ number oof turns of coil

⇒ **Some cases:**

Condition	Torque
$When\ \theta = 0°$ i.e. plane of loop is parallel to the direction of magnetic field.	$As\ \cos(0°) = 1 = maximum$ $\tau = nIAB \Rightarrow maximum\ value$
$When\ \theta = 90°$ i.e. plane of loop is perpendicular to the direction of magnetic field.	$As\ \cos(90°) = 0 = Zero$ $\tau = 0 \Rightarrow Zero\ or\ minimum\ value$

⇒ ***Expression of torque in terms of Magnetic moment of the current loop:***

$$\tau = nIAB$$

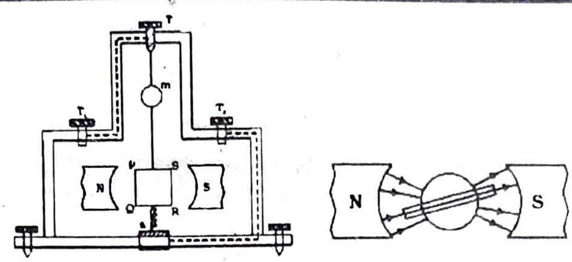
$$As\ nIA = Magnitude\ of\ magnetic\ moment\ of\ current\ loop\ \ so,$$

$$\tau = MBsin\theta \Rightarrow \vec{\tau} = \vec{M} \times \vec{B}$$

⇒ So, when a current carrying loop is placed in a uniform magnetic field, torque acts on it which tends to rotate the loop so as to align the $\vec{M}$ in the direction of magnetic field.

⇒ The unit of torque acting on a current carrying coil is; Nm.

Moving coil Galvanometer



⇒ The galvanometer is the main component in analog meters for measuring small current and voltage.

⇒ ***Principle:*** It uses a current carrying coil that rotates in a current carrying coil in a magnetic field (torque acts on it).

⇒ ***Components:***

1) Rectangular coil having large number of turns of insulated copper wire.
2) The coil is suspended between the poles of a powerful horseshoe magnet by a suspension fibre of phosphor-bronze. A spring is attached to the other end of the coil. The current enters the coil through the fibre and leaves the coil through the spring.
3) The upper end of the suspension fibre is connected to a rotating screw head so that the plane of the coil can be adjusted in any desired position.
4) The horseshoe magnet has cylindrically concave pole-pieces. Due to this shape, the magnet produces radial magnetic field so that when coil rotates in any position its plane is always parallel to the direction of magnetic field. When current flows through the coil it gets deflected.
5) A soft iron cylinder is fixed inside the coil such that the coil can rotate freely between the poles and around the cylinder. Due to the high permeability, the soft iron core increases the strength of the radial magnetic field.
6) A small plane mirror M is fixed to the suspension fibre. This along with lamp and scale arrangement is used to measure the deflection of the coil.

⇒ When a current to be detected through the coil is passed the coil experience a torque (Called deflecting torque). Through this the coil begins to torque.

$$Deflecting\ torque = \tau_d = nIABcos\theta$$

$$As\ field\ is\ radial, so\ plane\ is\ parallel\ to\ (0°) \Rightarrow Cos(0°) = 1 \Rightarrow \tau_d = nIAB$$

⇒ When a coil begins to turns, the phosphor bronze wire starts turning and produce another torque which is called restoring torque.

$$Restoring\ torque = \tau_c = k\theta\ (k\ is\ a\ constant\ called\ torsion\ constant)$$

$$\tau_c \propto \theta(twist)$$

⇒ The coil turns until $\tau_d = \tau_c$. They become equal.

⇒ As $\tau_d = \tau_c$

$$nIAB = k\theta \Rightarrow I = \frac{k\theta}{nAB} \Rightarrow I = G\theta \qquad As\ G = \frac{k}{nAB} = constant$$

so, $I \propto \theta$ (As current through the coil increased twist will be also increased).

⇒ ***Current sensitivity of galvanometer:*** *Deflection per unit current is called current sensitivity*

$$Current\ sensitivity, S_i = \frac{\theta}{I} = \frac{nBA}{k} \qquad As\ I = \frac{k\theta}{nBA}$$

Unit: *rad* A^{-1} *or div* A^{-1}

⇒ ***Voltage sensitivity of galvanometer:*** *Deflection per unit voltage is called current sensitivity*

$$Voltage\ sensitivity, S_v = \frac{\theta}{V} = \frac{\theta}{IR} = \frac{nBA}{kR}$$

R = *resistance of galvanometer*

Unit: *rad* V^{-1} *or div* V^{-1}

To increase sensitiviity of Galvanometer:

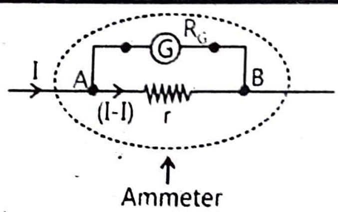
The sensitivity of a galvanometer can be increased by:

- ✓ increasing the strength of B
- ✓ *increasing the area of a coil*
- ✓ *increasing the number of turns in the coil*
- ✓ *Decreasing the torsion constant k of the spring*
- ✓ *Decreasing the resistance of galvanometer*

Problems asociated with increasing Sensitivity of galvanometer

- ✓ The small value of k means week suspension.
- ✓ By increasing the area, the coil will become bulky.
- ✓ By increasing the number of turns this will increase resistance of coil.

Conversion of galvanometer into Ammeter



⇒ We need to convert galvanometer into ammeter to increase the value of current measurement (to make Galvanometer which can measure large current), so for this ***we convert Galvanometer into ammeter by the help of connecting shunt resistance in parallel.***

⇒ Shunt have low resistance.

⇒ Sometime shunt is used to increase the range of an ammeter.

⇒ As the value of shunt is small so the resistance of ammeter will be greater.

⇒ Ammeter is connected with circuit in series.

⇒ ***Value of shunt resistance is given by;***

$$Shunt\ resistance, R_s = \left(\frac{I_g}{I - I_g}\right) G$$

Where G is resistance of galvanometer, I_g is current through galvanometer.

⇒ ***Value of Resistance of Ammeter is given by;***

$$Ammeter\ Resistance;\ R_A = \frac{GS}{G + S}$$

$G \rightarrow$ *Resistance of galvanometer*

$S \rightarrow$ *Shunt resistance*

⇒ Hence the value of $R_{Ammeter} < R_{shunt}$ *(Shunt Resistance)*

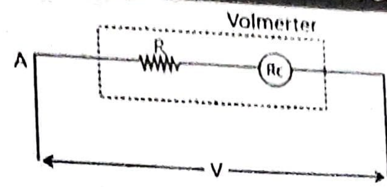
⇒ ***Full scale deflection current is given by;***

$$Full\ scale\ deflection\ current, I_g = nk$$

n = *number of scale division in galvanometer*

k = *current for one scale deflection in the galvanometer*

Conversion of galvanometer into Voltmeter



- ⇒ If we connect a high resistance in series with galvanometer then it is called Voltmeter.
- ⇒ Voltmeter is generally connected in parallel with the circuit
- ⇒ The High resistance is generally called multiplier.
- ⇒ The value of high resistance (Multiplier) is in range of kilo ohms.
- ⇒ As the value of multiplier is very large, value of resistance of voltmeter will be also large.

$$Resistance\ of\ Multiplier \propto Resistance\ of\ Ammeter$$

- ⇒ ***Value of high resistance/ Multiplier is given by;***

$$R_{High}(Multiplier) = \frac{V}{I_g} - G$$

- ⇒ ***Value of Resistance of Voltmeter:***

$$R_{voltmeter} = G + R$$

- ⇒ Hence the value of Voltmeter resistance is generally greater than that of Multiplier.

FORMULAS SHEET

1.	Magnetic force on current carrying conductor	$\vec{F} = I(\vec{L} \times \vec{B})$	$\vec{F} = ILB\ sin\theta\hat{n}$	$F = ILB\ sin\theta$
2.	Magnetic induction	$B = \frac{F}{IL}$	$B = \frac{F}{qv}$	
3.	Magnetic flux	$\phi = \vec{B}.\vec{A}$	$\phi = BA\ cos\theta$	
4.	Magnetic flux density	$\sum_{i=1}^{n} (\vec{B}.\Delta\vec{l}) = \mu_o I$	$B = \frac{\mu_o I}{2\pi r}$	
5.	Magnetic field due to solenoid	$B = \mu_o nI$	$B = \mu_o \frac{N}{l} I$	
6.	Magnetic force acting on a charge particle moving in magnetic field	$\vec{F} = q(\vec{v} \times \vec{B})$	$\vec{F} = qvB\ sin\theta\hat{r}$	$F = qvB\ sin\theta$
7.	Lorentz force	$F = F_e + F_b$		
8.	e/m value of electron	$\frac{e}{m} = \frac{v}{Br}$	$\frac{e}{m} = \frac{2V}{B^2r^2}$	
9.	Velocity selector	$v = \frac{E}{B}$		
10.	Torque acting on current carrying loop in magnetic field	$\tau = IBA\ cos\alpha$		
11.	Torque acting on current carrying coil in magnetic field	$\tau = NIAB\ cos\alpha$		
12.	Deflecting torque acting on galvanometer coil	$\tau = NIAB$		
13.	Restoring torque acting on galvanometer coil	$\tau = C\theta$		
14.	Torsional constant	$\tau = \frac{C}{\theta}$		
15.	relation between current and deflecting angle in galvanometer	$I = \frac{C}{BAN}\theta$		
16.	Shunt resistance for conversion of galvanometer into ammeter	$R_s = \frac{I_g R_g}{I - I_g}$		
17.	High resistance for the conversion of galvanometer into voltmeter	$R_h = \frac{V}{I_g} - R_g$		

UNITS

1.	Magnetic induction	$Nm^{-1}A^{-1}$	*tesla*
2.	Magnetic flux	NmA^{-1}	*weber*
3.	Magnetic flux density	Wb/m^2	$Nm^{-1}A^{-1}$
4.	Permeability of free space (μ_o)	$Wbm^{-1}A^{-1}$	
5.	Relative permeability (μ_r)	*no unit*	
6.	e/m value of electron	C/Kg	
7.	Torsional constant (c)	Nm/rad	

Some important points and tricks

1) Magnetic field at the ends of a long current carrying solenoid is half of that at the centre.
2) Magnetic field inside a long straight solenoid is independent of the length and diameter of the solenoid and is uniform over the cross-section of the solenoid.
3) The magnetic field produced due to current through a conductor is always in a plane perpendicular to the plane of the conductor.
4) The magnetic Lorentz force does no work on the charge, as it always acts perpendicular to the direction of motion of charge.
5) Magnetic field has three properties
   i. It is only due to moving charges. In this you can remember if

Condition	Result
charge is stationary	only electric field
charge is moving with uniform velocity	electric field and magnetic field
charge is moving with accelerated motion	electric field, magnetic field and electromagnetic radiations

   ii. Any charged particle in magnetic field will always move in a circular path.
   iii. Since magnetic force is given by the formula $\vec{F} = q\vec{v} \times \vec{B}$.
6) A charge always experiences a force in electric field, whether it is stationary or in motion.
7) In a magnetic field, a stationary charge does not experience any force, while a moving charge experiences force, provided it is not moving parallel to the direction of the field.
8) Electric force is an absolute concept while magnetic force is a relative concept for an observer.
9) Magnetic force is velocity dependent, while electric force is independent of the state of rest or motion of the charged particle.
10) The value of magnetic field induction at a point, on the center of separation of two linear parallel conductors carrying equal currents in the same direction is zero.
11) If a magnetic needle is kept in a uniform magnetic field, then it experiences only torque, not a force.
12) In non-uniform magnetic field, magnetic needle experiences both torque and force.
13) The positive ions are produced in the gap between the two dees by the ionization of the gas. To produce proton, hydrogen gas is used; while for producing alpha-particles, helium gas is used.
14) The energy of a charged particle moving in a uniform magnetic field does not change because it experiences a force in a direction, perpendicular to its direction of motion due to which, the speed of charged particle remains unchanged and hence its K.E. remains same.
15) Time period of revolution of a charged particle inside the dees (magnetic field) is independent of the speed and radius of the circular path described. It depends upon the value of its charge, mass and strength of the field.
16) If a particle enters a magnetic field normally to the magnetic field, then it starts moving in a circular orbit. The point at which it enters the magnetic field lies on the circumference. (Most Of us confuse it with the centre of the orbit).
17) Accuracy of suspended type MCG can be increased by increasing distance between galvanometer and lamp and scale arrangement.
18) Accuracy of pivoted type MCG can be increased by increasing height of pointer.
19) Multimeter is a single device which can measure potential difference, current and resistance. It is a modified form of moving coil galvanometer.
20) Ohmmeter measures resistance and is a modified form of MCG.
21) A voltmeter cannot be used to measure emf of the cell.
22) A voltmeter can measure D.C. voltage only. To measure A.C. voltage, rectifier circuit is connected before voltmeter.
23) Lorentz force is maximum, when the charged particle moves at right angles to the field. The force is zero when the charged particle is at rest or moving parallel or antiparallel to the field, where R = radius of dees.
24) Whenever there is a question involving ammeter or shunt, just look for two values in the given question and always apply the formula,

$$\frac{Smaller\ value}{Bigger\ value} = \frac{S}{S+G}$$

where S is shunt which is very small and G is resistance of galvanometer.

25) If in the question two values of current are given, always remember the bigger value will be I and the smaller value will be I_g.

26) If in the question only one value of current is given, remember it will always be I_g.

27) It in the question, it is given that x% of main current passes through galvanometer, then simply apply the formula $\frac{I_g}{I} = \frac{x}{100}$.

28) In formula $R = \frac{V}{I_g} - G$ V is new range (for

Example: if galvanometer was able to read up to 10 volts and it is to be converted into voltmeter to read up to 100 volts, then V will be 100 volts) and to calculate Ig always apply the formula

$$I_g = \frac{Old\ range}{G}$$

29) For a voltmeter, value of R should always be very high and value of S should be very small.

30) In order to reduce the range of voltmeter of resistance G from V to V/n, a shunt equal to nG should be connected in parallel with it.